

Feasibility of a fully autonomous wireless monitoring system for a wind turbine blade



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ABSTRACT

Condition monitoring (CM) of wind turbine blades has significant benefits for wind farm operators and insurers alike. Blades present a particular challenge in terms of operations and maintenance: the wide range of materials used in their construction makes it difficult to predict lifetimes; loading is stochastic and highly variable; and access can be problematic due to the remote locations where turbines are frequently located, particularly for offshore installations. Whilst previous works have indicated that Micro Electromechanical Systems (MEMS) accelerometers are viable devices for measuring the vibrations from which diagnostic information can be derived, thus far there has been no analysis of how such a system would be powered. This paper considers the power requirement of a self-powered blade-tip autonomous system and how those requirements can be met. The radio link budget is derived for the system and the average power requirement assessed. Following this, energy harvesting methods such as photovoltaics, vibration, thermal and radio frequency (RF) are explored. Energy storage techniques and energy regulation for the autonomous system are assessed along with their relative merits. It is concluded that vibration (piezoelectric) energy harvesting combined with lithium-ion batteries are suitable selections for such a system.

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1. Introduction

Energy harvesting is the process by which low-density ambient energy is captured, converted and stored, if necessary, to provide low-power generation for powering electronic devices [1,2]. Solar, thermal, mechanical and electromagnetic radiation are the most common sources for harvesting electrical energy from the environment. Not all of these sources, such as solar and thermal energy, are available all the time so it is necessary to incorporate a storage device to power the system for continuous operation. The introduction of a storage element has the disadvantage that devices such as batteries have a limited lifespan, so it is necessary to take this into account if the system is to be fitted for the lifetime of a mechanical component such as a wind turbine blade.

There has been renewed interest in power harvesting in recent years which has been driven by advances in transducer technology, improvements in storage devices and the ready availability of custom integrated circuits (ICs) for power management. The devices often benefit from a miniature size, ease of installation, flexibility, suitability for retrofitting and their very low cost. The compact nature of these devices and lack of dependence on a permanent power source make them good candidates for installation in remote locations and indeed in places where it would not normally be considered feasible to install an autonomous system. The present paper presents a technical analysis of a fully autonomous monitoring system placed right on (or within) a wind turbine blade near to the tip for the purpose of monitoring its condition [3,4]. Whereas previous work has established the feasibility of using low cost MEMS accelerometers to assess the modal properties in experimental studies of small to medium sized turbine blades [5,6], the present paper focuses on the issue of providing a power source to such a system and its design parameters. Another important contribution of the present paper over previous works is consideration of the detailed requirements of such a system and

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providing calculations of the radio link budget. The link budget has a close relationship with the power requirement as it is a major source of energy loss from the autonomous system. The problem is challenging as the radio power required varies as the machine turns and there are potential power savings that can be achieved by controlling the transmit power in sympathy with the transmitter's position. This problem is not presently addressed in the literature.

Condition monitoring (CM), which is the continual sensing of parameters affecting machine operation to provide early warning of reliability issues, is well understood for large, constant speed rotating machines but has only recently been investigated for wind turbines. Condition monitoring of wind turbines presents a substantial engineering challenge due to the presence of both low speed and high speed rotating shafts, as well as highly dynamic vibrations in torque and speed [7–12]. Vibration-based condition monitoring techniques are the most widely employed and can be used to monitor components such as the gearbox, generator, bearing and blades. Vibration-based systems are based on the principle of relating the resonant properties of a structure to its physical properties. Changes in the physical properties of a structure (mass, stiffness and damping properties) can cause changes in resonant properties of that structure such as the natural frequency, modal damping and mode shape [5,6,13–19]. A number of different techniques have been proposed for the monitoring of wind turbine blades [20], however, this paper focuses on the design parameters and feasibility of an autonomous system that could be used for modal analysis.

Specifically, this paper considers the issues surrounding the installation a wireless monitoring system within a wind turbine blade, which is fully self-contained, self-powered and able to transmit data concerning the condition of the blade to a base station on the ground. Such a system has various technical challenges, such as the provision of a power supply which can outlast the service life of the blade and the availability and location of sensors such as accelerometers that can be deployed within the structure to measure the various properties of the blade during operation. In addition to the power and electronic requirements, a strategy for monitoring and signal processing the received data is also worthy of consideration. The present paper covers the fundamental power requirements of such a system and the feasibility of providing this power using energy harvesting devices located within or on a blade. It explores the energy requirements necessary to acquire frequency domain statistics such as Fast Fourier Transforms (FFTs) and transmit this vibration data. Section 2 describes the autonomous low-cost wireless system components and the operation. Section 3 describes the power requirements of the system and the radio link budget, Section 4 describes the energy sources considered for powering the system, Section 5 provides analysis of some commercially available energy harvesters and finally Section 6 offers conclusions and recommendations.

2. Description of the autonomous system

Esu et al. [5,6,16] describe the use of MEMS accelerometers for detecting the vibrations of wind turbine blades. The widespread use of MEMS accelerometers in smartphones [21] and for airbag deployment in the automotive industries has decreased their cost and made them readily available. The CM system described in this paper capitalises on these merits. The autonomous wireless CM system comprises of a number of small (dimension: 4 mm × 4 mm × 1.45 mm) surface micro-machined capacitive ADXL335 [22] MEMS accelerometers that measure acceleration in 3-axes with a full-scale range of ±3 g (where 1 g = 9.81 ms⁻²) and have a power consumption of 1 mW when supplied with a nominal voltage of 3 V [23–28].

The accelerometers detect and measure the vibration of the blade to which they are affixed and the measured data are logged using a 16-bit high performance dsPIC33F Microchip [29] digital signal microcontroller. The Microchip dsPIC33FJ128MC802 microcontroller [29] was chosen because of its low power consumption, digital signal processing capabilities and its operating voltage of 3.3 V. These devices also provide a real-time response, have a flash memory of up to 128 KB and a CPU speed of 40 MIPS. They perform well in harsh environments and can withstand vibrations [30]. The microcontroller has a watchdog timer and extensive power management functionality with idle, sleep and doze modes with fast wake-up features at low current consumptions (~nA). These features or equivalents are also available in devices from other manufacturers, however the one chosen is typical of a class of low power microcontrollers with signal processing capability.

The microcontroller samples the measured data and performs a FFT on them ready for wireless transmission. A wireless RF transmitter module [31] which has a current consumption of 8 mA at 3 V is connected to the microcontroller and the transformed data, composed of peak frequency and amplitude, are transmitted to a remote ground-based receiver and computer, where performance plots are displayed to indicate the state of health of the wind turbine blade. The desired specification for the system is to display a spectrum from 0 to 500 Hz. Analysing vibration data in the frequency domain provides a useful indication of the blade health and enables the identification of impending failures from its characteristic vibration signature [5,32–35].

The microcontroller is able to selectively power the RF circuits according to the accumulated charge on the systems storage unit by integrating the voltage applied to the storage unit with respect to time whilst in a low power mode. The energy regulator is able to signal to the microcontroller when the power supply is good from the energy harvester and in addition the microcontroller is able to manage the operation of the regulator and can shut it down in the case that the storage unit is full. Thus the function of the system can be fully managed by the microcontroller, which can also choose to perform computationally intensive signal processing only when adequate energy is available in the storage unit. Fig. 1 illustrates the architecture of the condition monitoring device. After measuring vibrations and transmitting the data to the base station, the device goes into sleep mode until the next measurement to save power. In sleep mode, the current consumption of the microcontroller is very low since the microcontroller only needs to monitor the state of charge on the storage unit.

3. Predicted power consumption

3.1. Radio channel link budget

Consider the system geometry shown in Fig. 2.

The power at the ground based receiver is thus:

$$P_R = P_T + G_T - L_T - L_{FS} - L_M + G_R - L_R \quad (1)$$

where P_R is the received power in dBm. G_T and G_R are the antenna gains of the transmitter and receiver in dBi, L_R and L_M are loss factors in dB for miscellaneous mechanisms such as a polarization mismatch between transmitter and receiver.

The term L_{FS} is the free space radiation loss associated with the radio channel and is a function of transmit frequency, f and the distance of the link, d in m. If the speed of radio propagation in air is $c \approx 3 \times 10^8$ m/s then the loss is given by Friis' formula:

$$L_{FS} = 10 \log_{10} \left(\frac{4\pi}{c} df \right)^2 = 20 \log_{10} \left(\frac{4\pi}{c} df \right) \quad (2)$$

Expanding this gives:

$$L_{FS} = 20 \log_{10} \left(\frac{4\pi}{c} \right) + 20 \log_{10}(d) + 20 \log_{10}(f) \quad (3)$$

If frequency, f , is expressed in MHz and the distance, d , is in m the loss in dB is given as:

$$L_{FS} = 20 \log_{10} \left(\frac{4\pi}{c} \right) + 20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}(10^6) \quad (4)$$

which can be reduced to:

$$L_{FS} = -27.55 + 20 \log_{10}(f) + 20 \log_{10}(d) \quad (5)$$

This equation assumes spherical spreading of the wavefront emitted from the on-blade system which is a realistic assumption for a small antenna.

A practical antenna to use in a rotating system has pattern symmetry in one of its cardinal planes. This way when the device undergoes rotation the received signal is not adversely affected. Here we assume a monopole antenna which meets that

requirement with a gain $G_T = 5.19$ dBi. The receive antenna can be of various types, however, a commonly used patch antenna with unidirectional pattern and G_R of approximately 9 dBi would seem a reasonable choice due to its beam shape.

The distance d for the link is not a fixed value and varies according to the blade's angular position. Thus, the link budget will vary accordingly. For an assumed hub height of 95 m and rotor diameter of 90 m, $50 \text{ m} < d < 140 \text{ m}$. The free space loss variation during a full cycle with the receiver directly under the hub is $20 \log_{10}(140) - 20 \log_{10}(50) = 8.94$ dB. The receiver deployed in such a system must be able to handle this dynamic range and these distances.

To determine the transmit power, and hence the radio energy requirement, it is necessary to assume a particular receiver sensitivity. A typical benchmark figure for receiver sensitivity would be -70 dBm, although in some frequency bands and devices it may be -110 dBm or even better. Taking the worst figure of -70 dBm, a frequency of 2.45 GHz and the dimensions given above the transmit power can be determined:

$$P_T = P_R - G_T + L_T + L_{FS} + L_M - G_R + L_R \quad (6)$$

If we assume that the connector/mismatch losses and miscellaneous losses are negligible and by substituting from (5) then,

$$P_T = P_R - G_T - 27.55 + 20 \log_{10}(f) + 20 \log_{10}(d) - G_R \quad (7)$$

Hence for the given quantities and the largest value for d we get the transmit power to be approximately -1.04 dBm. This corresponds to a power of 0.787 mW delivered into a 50 Ω load.

The analysis assumes the worst case of the transmitter and

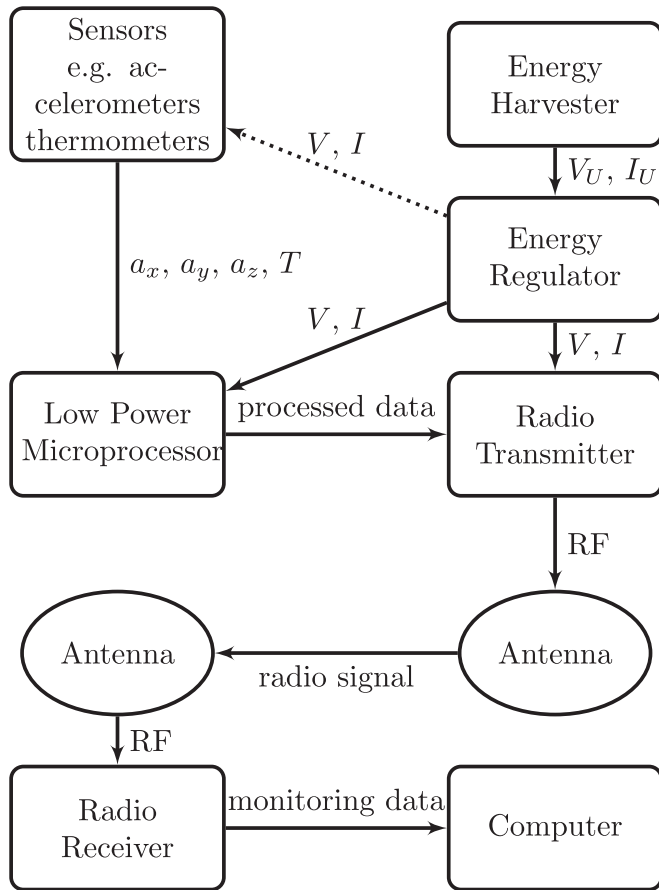


Fig. 1. Architecture of the wireless monitoring system for in-situ wind turbine monitoring. Dotted link indicates a necessary link for active sensors such as packaged MEMS accelerometers. Subscript U indicates unregulated voltages and currents which may be a.c. or d.c. quantities. a_x , a_y , a_z , are readings from the 3 axes of a triaxial accelerometer and T is the temperature.

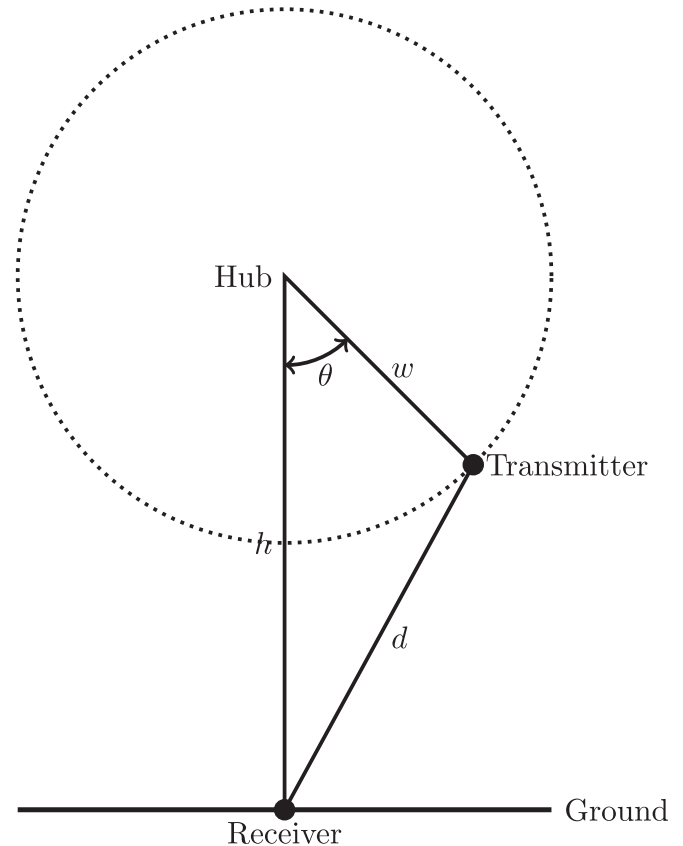


Fig. 2. Geometry used for the link budget calculation on a blade-tip mounted transmitter.

receiver being at the greatest value of d . If some sort of power control could be affected on the transmitter, there is the possibility of modulating the output power according to the position of the blade at a given time. Turning attention back to Fig. 2, the distance can be calculated by taking the blade radius, w and the hub height, h and considering the distance between the transmitter and receiver. It can be shown that,

$$d(\theta) = \sqrt{h^2 + w^2 - 2hw \cos(\theta)} \quad (8)$$

The average distance between transmitter and receiver can be calculated by integrating over half of the circle,

$$d_{av} = \frac{1}{\pi} \int_{\theta=0}^{\theta=\pi} d(\theta) d\theta \quad (9)$$

which can be evaluated numerically by computing a complete elliptic integral function of the second kind, $E(m)$. For the case where $h = 95$ m and $w = 45$ m the integral to be computed is:

$$d_{av} \approx \frac{1}{\pi} 280E\left(\frac{171}{196}\right) = 100.4 \text{ m} \quad (10)$$

The average transmit power required is therefore calculated as before but using d_{av} in place of d giving -3.93 dBm which is 0.405 mW. Thus there is a potential saving of approximately a half if power control can be achieved in the radio system. Note that this calculation assumes that the transmitter remains in the main beam of the receive antenna which is a reasonable assumption given the range of the receiver in all of its possible positions and the $\approx 65^\circ$ beam width of the patch antenna. The system might be conceived with different frequencies of operation taken from the Industrial, Scientific and Military (ISM) bands which offer unlicensed radio spectrum. A selection of these bands along with their bandwidths and worst-case transmit powers are included in Table 1. As would be expected from (7) the power required is lower at lower frequencies, however it must be borne in mind that lower frequencies are associated with larger antennas (for a given antenna efficiency and bandwidth) and hence there may be a trade off between the power consumption and the physical dimensions of the device.

Providing this power to facilitate the radio link, plus whatever power is required by the microcontroller and sensor system is the focus of the remainder of this paper.

3.2. Electronic components

The current consumption of the components described in Section 1 was measured experimentally and the results are shown in Table 2. The total power consumption was 26 mW. It is worth noting that the microcontroller was not executing any program when the current measurement was taken. Experiments suggest that during intensive computation the current consumption

Table 1

Approximate transmit power required for a variety of wireless frequencies in the Industrial, Scientific and Medical (ISM) bands [36]. It is assumed that the receiver sensitivity is -70 dBm and the maximum transmit distance is $d = 140$ m.

Usage	Freq. (MHz)	Bandwidth (MHz)	Power (mW)
Short range	433.92	1.74	0.0247
Cordless telephony	915	26	0.1099
Bluetooth	2450	100	0.7881
Hiperlan	5800	150	4.4168

increases to 5 – 6 mA. In a particular application it would be necessary to consider how much processing is required by the monitoring system or alternatively the data may be transmitted to the ground station for post processing where fewer power constraints apply. It is clearly challenging to make generalisations about the system beyond the architecture, except to observe that some typical readily available commercial components offer low standby power consumption. These devices can be designed to wake up from an idle state when sufficient power becomes available. This option may be acceptable for most turbine monitoring operations where data may not be required continuously.

The remaining sections focus strictly on the power requirements for the autonomous wireless CM system, energy harvesting, storage and regulation.

4. Energy sources

4.1. Harvesting

Several energy harvesting methods were considered for the autonomous low-cost wireless condition monitoring system. In this section, their operation, advantages and disadvantages for application in the autonomous system are discussed.

4.1.1. Photovoltaic (PV) cells

PV cells convert sunlight into electricity with power ratings in the order of mW for a single cell to hundreds of Watts for a large module [37–39].

Advantages: Cells have a relatively long lifetime with no moving parts; they can be easily attached to a turbine blade, particularly if they are of the flexible thin film type; cells are light and size is scalable; cost is modest even for small scale application ($\$$ 4–5 per Watt); and output is d.c.

Disadvantages: The output is highly variable as the cells do not operate during nighttime and the power is reduced during cloudy conditions; the cells cannot be mounted inside the blade; on a blade which rotates attached to a turbine which yaws into the wind, the cell will frequently not be in an optimal position relative to the sun; if the cell projects too far from the blade surface, it may affect the aerodynamics of the blade; fouling of the cell over time will reduce efficiency; and performance will naturally degrade with time.

4.1.2. Piezoelectric devices

Piezoelectric devices make use of a resonant beam which generates electricity when subjected to strain caused by vibration or motion, thereby generating a voltage [40–43].

Advantages: Devices are light weight; energy harvesting efficiency is well maintained over a long time period (unless the maximum tip to tip displacement is exceeded); the frequency of vibration of the beam can be adjusted or tuned to suit the wind turbine blade; devices are available in various sizes and can be positioned in/on the wind turbine blade easily.

Disadvantages: Output is a.c. which needs to be rectified; the devices flex and can thus fatigue over time; as the piezoelectric harvester feeds off the vibrations of the turbine blade, they can only

Table 2

Measured current consumption of typical devices used in the autonomous system. The test conditions used for these measurements are described in the text.

Device	Current consumption	Voltage
Accelerometer	355 μ A	3.00 V
Microcontroller	287 μ A	3.27 V
RF transmitter	8 mA	3.00 V

work when there is sufficient wind (although this is generally when there is greatest need to monitor the blade); and they are relatively expensive at current prices (~\$5000 per Watt based on a peak power output of 10 mW for a ~\$50 device.).

4.1.3. Electromagnetic harvesters

These devices also convert vibration energy into electrical energy. The relative motion of a magnetic mass in the transducer with respect to a coil causes a change in the magnetic flux. This generates an a.c. voltage across the coil [40,44].

Advantages: Electromagnetic energy harvesters can be placed in/on wind turbine blades easily with no connection problems.

Disadvantages: Such devices are bulky, which could interfere with the aerodynamics of the blade if externally mounted; the output power is low from some devices; and moving parts are susceptible to fatigue and failure.

4.1.4. Thermal energy harvester

Thermal energy harvesters such as a thermocouples operate based on the Seebeck effect, i.e. when two junctions made of two dissimilar conductors are kept at different temperatures, an open circuit voltage develops between them [40]. Heat loss due to mechanical friction within the nacelle (which houses the gearbox etc.) of a wind turbine blade could be harvested using thermal energy harvesters.

Advantages: Devices are relatively low cost; they are light; and the energy dissipated in the nacelle provides a constant source of energy.

Disadvantages: Thermal energy harvester output will be variable due to the variance in temperature in the nacelle; connection through the hub to the accelerometers adds to complexity and cost.

4.1.5. RF energy harvester

Radio frequency energy available through public telecommunication services (e.g., GSM and WLAN frequencies) is converted to electrical energy [40,45,46]. The technology is restricted to a band where there is sufficient ambient power, for example, 902–928 MHz [47].

Advantages: Devices are potentially low cost; they can be placed easily on (or in) the wind turbine blade.

Disadvantages: The power density available is small, requiring a large antenna aperture to capture even small amounts of power; wind turbines are located far away from areas of high population density, therefore there will be little RF energy to harvest; power output is low.

Based on the above discussion, photovoltaics and piezoelectric energy harvesters were seen as the most viable options to power an autonomous blade CM system. Electromagnetic energy harvesters were a possible consideration, however, they are difficult to utilize and limited technology is available on the market at present.

4.2. Storage

Storing the excess energy generated by the harvesters is essential to ensure uninterrupted operation of the microcontroller when performing operations such as turning on the transmitter, acquiring or signal processing the data. Voltage, charge storage capacity, charge cycling, lifetime, cost, size and weight were examined to identify the most suitable choice for the storage of energy. Energy storage methods and techniques for the autonomous low-cost wind turbine blade condition monitoring system are considered below.

4.2.1. Chemical storage

Batteries are the most widely used chemical storage of electrical

energy. Rechargeable batteries may be charged by the energy harvester to power the autonomous CM system. Numerous battery chemistries are available, however the most widely depolyed and readily available are lithium ion batteries [48]. The energy densities available from batteries is significantly higher than capacitors, however, batteries are only capable of a finite number of charge/discharge cycles. Some battery chemistries are also affected by the memory effect (e.g. Nickel-Cadmium) which can degrade performance if they are not deep cycled periodically, whilst others (e.g. Lithium Ion) prefer not to be deep cycled. This could be managed by the microcontroller if required.

Advantages: They provide high charge capacity per unit volume at a reasonable cost; and there is a large choice available in terms of size, voltage and capacity.

Disadvantages: They can be bulky and degrade over time; disposal contributes to environmental waste; and lifetime may be a limiting factor.

4.2.2. Charge storage

Capacitors or supercapacitors could provide a modest amount of electrical energy storage, when insufficient power is generated by the energy harvesting device for a limited period of time.

Advantages: They are lightweight; there is a large choice available in terms of capacity and voltage.

Disadvantages: Cost is high per unit energy stored; and capacity is quite limited.

4.2.3. No storage

Potentially, the energy harvesting device could be directly coupled to the autonomous CM device without any energy storage.

Advantages: This is a low cost, simple solution which avoids the limited longevity associated with batteries.

Disadvantages: This method may constrain the choice of energy harvester to be used; and loss of data can be expected when the harvester is unable to provide enough power for the CM device.

In conclusion, the preferred solution is to use capacitors as the storage medium due to their long service life, however due to the energy density and cost of such devices, batteries will be considered in the remainder of this paper.

4.3. Regulation

In order to charge the storage units and to provide an output at a constant voltage suitable for operating the sensors, microcontroller and transmitter a regulator must be provided. Linear regulator ICs are one option as low dropout devices are available. However, generally they are suitable for higher power applications. Commercial regulators designed for power harvesting are available and these are the preferred options, since apart from being optimised for low power operation, they also provide control pins (SHDN and PGood) which interface with the microcontroller. Internally, the devices consist of a switching regulator and are designed specifically for a particular harvesting technology. An example of such a regulator circuit showing the device and its external component is given in Fig. 3.

5. Evaluation of commercial energy sources

5.1. Photovoltaic panels

A SLMD481H10L photovoltaic cell [50] was selected as a typical high performance monocrystalline device with an efficiency of approximately 22%.

Fig. 4 shows the measured power density during the winter period 2012–13 based on data acquired in the UK midlands for a

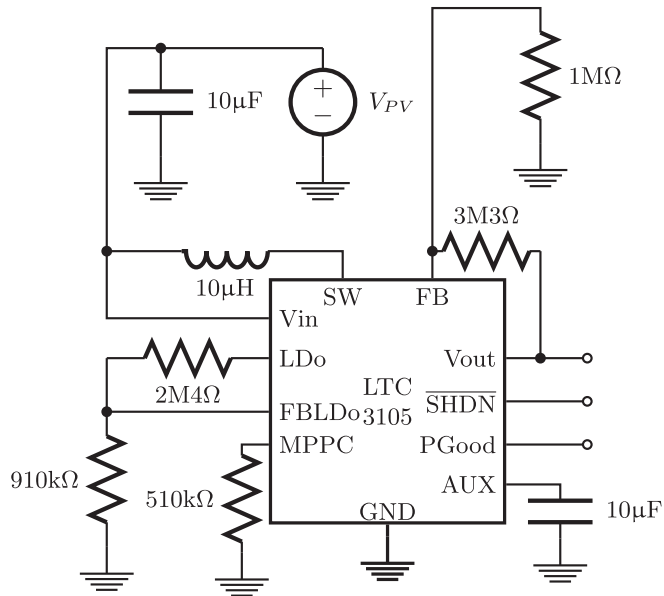


Fig. 3. Schematic of the photovoltaic circuit adapted from Ref. [49]. V_{out} , \overline{SHDN} and P_{Good} signals are all routed to the microcontroller.

horizontal planar device. The average power that would be received by the device chosen would be 38 W per m^2 . Taking into account the device efficiency and area, this equates to a average power output of 50 mW assuming an optimal solar cell orientation. This is approximately double the power requirement of the system under discussion.

5.2. Piezoelectric energy harvester

A Midé Vulture (type V21BL) [51] piezoelectric vibration energy harvester was investigated. It comprises of two electrically isolated piezowafers which may be used independently or bridged for increased voltage (series configuration) or current output (parallel configuration). A parallel configuration was used because higher current was preferred for the regulator configuration chosen for the system. One restriction of cantilever devices is that they have distinct resonances which have to be matched to frequency bands where there is sufficient energy in the vibrating structure. Tuning of

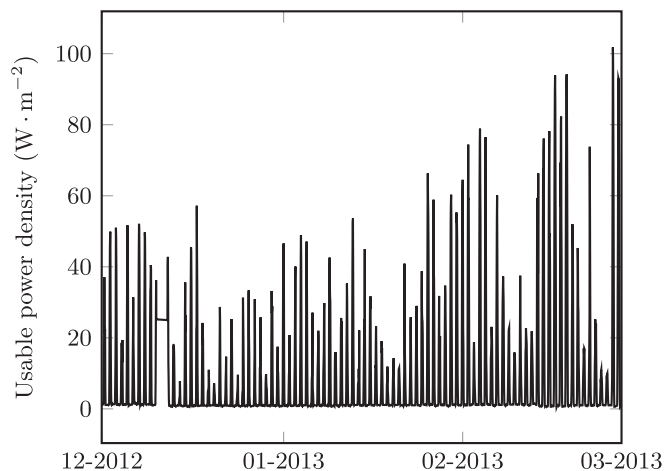


Fig. 4. Usable solar power from panel in the UK (Midlands) during the winter of 2012–13.

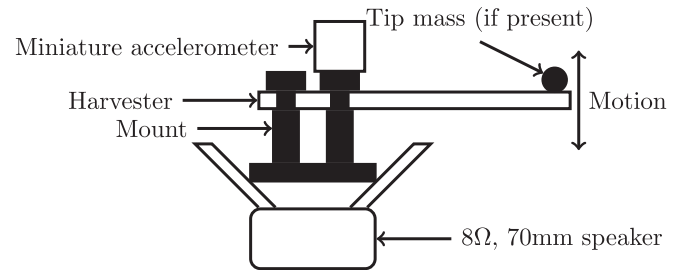


Fig. 5. Experimental setup for measuring the piezo energy harvester simulating wind turbine vibrations.

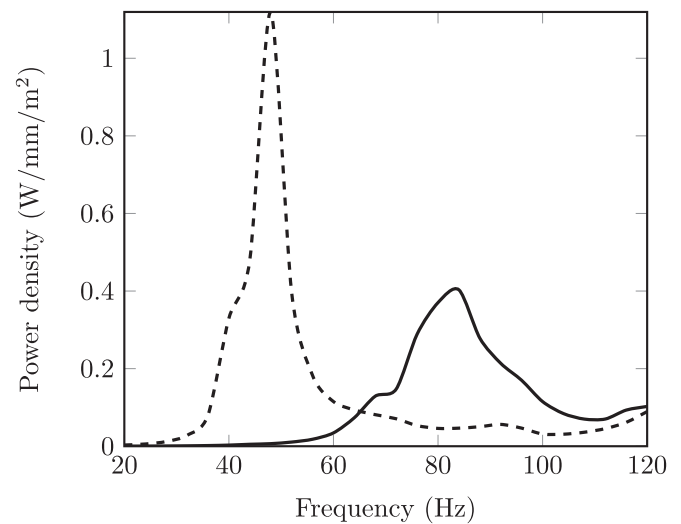


Fig. 6. Power density achieved for type V21BL device expressed per mm of displacement of the affixed object. Comparison between the untuned device frequency response (solid line) and the tuned frequency response for a 10^{-3} kg tip mass (dotted line).

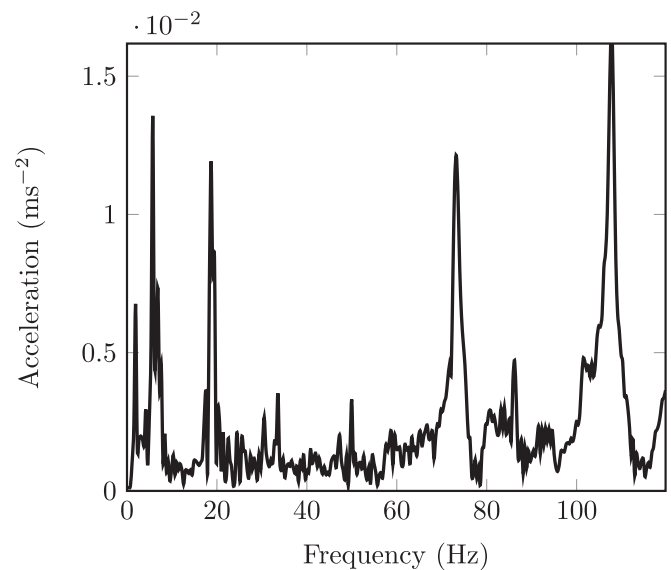


Fig. 7. Frequency response of a 4.5 m long blade from a 25 kW Carter wind turbine measured near to the blade root. The excitation was applied using a force hammer near to the tip.

the device can be achieved by attaching a small mass to the tip of the device. An experiment was devised (Fig. 5) to measure the effect of tip loading on a mounted V21BL device. The arrangement was driven from a variable frequency sinusoidal voltage source and feedback from the accelerometer was used to maintain a constant peak acceleration of 4.2 m/s^2 across the frequency range of interest. The data was subsequently normalised with respect to the displacement seen at the accelerometer, obtained by double integrating the acceleration. Also, the data was normalised with respect to the area of the device to represent the power density for a 1 mm displacement of the vibrating surface being harvested. The result of loading can be seen in Fig. 6. As would be expected, the natural frequency of the device has been successfully lowered. Now we consider how this device would be applied to a turbine blade.

Generally, large scale wind turbine blades (i.e. 40 m and above in diameter) have their first natural frequencies in the range of 0.5 Hz–15 Hz [15]. In addition, the turbulent characteristics of the wind will produce higher frequency forcing vibrations, some of which may excite higher order vibrational modes. This, therefore, means that the piezoelectric energy harvester should be tuned to suit the vibrational characteristics of each individual turbine blade. An example result from a medium sized blade from a Carter wind turbine can be seen in Fig. 7. It can be seen that the modal frequencies of the blade extend considerably above the fundamental and in particular there is a mode at 70–80 Hz which is within the tunable range of the harvester characterised in Fig. 6.

In further tests by varying the loading and by utilising a compatible voltage regulator optimised for piezoelectric energy harvesting, type LTC3588EMSE [52] a maximum power output of 10 mW can be achieved at 1 g acceleration. This meets the 1 mW power requirement for each MEMS accelerometer. However, a cluster of these piezoelectric energy harvesters would be needed to meet the system requirements. During experiments the manufacturer's suggested maximum limit of 4 mm deflection at the tip was not exceeded, something which would have to be carefully considered if such a system were deployed in the field.

6. Conclusion

This paper has introduced the concept of a fully autonomous monitoring system for a wind turbine blade which has its own in-built power source. A fundamental difference between the system proposed and commercial systems is the purpose—while commercial systems focus on ice detection and loading, the proposed system focuses on damage detection. The major power requirement of such a damage detection system is to provide radio frequency transmission power of the vibrational data from each of the blades to a ground station. The main difference between the system proposed when compared to a typical commercial system used for ice-loading is that the measurement transducer, energy harvesting, processing and data transmission elements can, if desired, all be easily encased within the blade as they require no maintenance.

A ground monitoring system to postprocess the output of the system is feasible, which is more convenient than fitting the unit within the nacelle where monitoring systems are sometimes installed. Nacelle based systems are straightforward enough when the components being monitored are in the nacelle. However, when on the hub or blades, there are added complications of slip ring connections. Ground monitoring keeps turbine technicians out of the nacelle, decreasing costs and increasing outputs; a goal for asset owners. Also, having a remote monitoring system opens up the possibility of monitoring multiple machines on a wind farm site from one unit. In order to conclude that such a system is indeed possible it has been necessary to evaluate a variety of factors.

A link budget has been presented to quantify this which takes

into account the rotating machine. The remainder of the power budget is consumed by a microprocessor and the sensors from which the data are to be collected. From the power supply options evaluated in more detail the photovoltaic cell provides the highest power density per unit area of device compared to the piezoelectric harvester. For the latter device it has been demonstrated that higher order vibration modes of a wind turbine blade could be coupled into the harvester with the selection of an appropriate device and by tuning. It is difficult to make a true like-for-like comparison between the harvesting technologies as they draw energy from two sources which are different in nature—the PV panel being active in fair weather with sunshine and the piezo device being active in windy weather. Either technology is likely to require a period to charge energy storage devices until there is sufficient energy available to make an energy transmission. The system can therefore be envisaged as an aperiodic rather than continuous device. There seems a strong argument that a piezo system has a major advantage over the PV since it does not require any external changes to a standard turbine blade. In addition, the piezo device can harvest energy when the turbine experiences the highest mechanical loading which is likely to be coincident with the times that the other sensors such as accelerometers are also active. In generally windy and possibly dull weather, the system would consequently be capable of performing the monitoring functions with the shortest time period between samples.

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